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6. AUTHOR(S)
S.S. Sastry

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Regents of the University of California
c/o Sponsored Projects Office
336 Sproul Hall
Berkeley, CA 94720-5940

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13. ABSTRACT (Maximum 200 words)

On this grant we worked on the hierarchical, hybrid adaptive control of multi-agent systems. The research has resulted in some spectacular new results in the following areas:
1) algorithms for hybrid control of multi-agent systems with proofs of correctness for safety procedures with applications to several practical systems.
2) techniques for consistent hierarchical models of complex systems; finite bisimulation results (exhaustive) of all finitely verifiable systems
3) nuerodynamic learning for complex hybrid systems with applications to realistic rendering of human motor actions.

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Design of Hierarchical, Hybrid, Adaptive Control Systems: Final Report

S. S. Sastry

September 2000

Abstract

On this grant we have worked on the hierarchical, hybrid adaptive control of multi-agent systems. The research results have resulted in some spectacular new results in the following areas:

1. algorithms for hybrid control of multi-agent systems with proofs of correctness for safety properties with applications to several practical systems.
2. techniques for consistent hierarchical models of complex systems; finite bisimulation results (exahustive) for all finitely verifiable systems
3. neurodynamic learning for complex hybrid systems with applications to realistic rendering of human motor actions.

1 Scientific Personnel Supported on the Grant

The scientific personnel supported on the grant so far are:

1. Jeff Wendlandt
2. Lara Crawford
3. George Pappas
4. John Lygeros
5. Frank Hoffmann
6. Mark Greenstreet
7. Max Holm
8. Cenk Cavusoglu
9. Shankar Sastry (PI)

Dr. John Lygeros and Dr. Frank Hoffmann were post doctoral researchers on the project. Dr. Jeff Wendlandt finished his PhD [22] in September 1997 , Lara Crawford [25] in September 1998, George Pappas [26] finished in November 1999 and Cenk Cavusolgu [27] in September 2000. Dr. Mark Greenstreet was a Visiting Professor from University of British Columbia. All scientific personnel supported on this program with the exception of Cenk Cavusoglu are US citizens.

2 Brief Summary of Research Findings

2.1 Nonlinear Control

We have worked on two topics here:

- Control of non-minimum phase systems with fast zero dynamics. In [2] we developed a new technique for tracking of nonlinear systems without cancellation of fast unstable modes.
- Control of Systems with Saturation. In [1] we developed techniques for trajectory planning for systems where the actuators may be saturated because of unacceptably agressive trajectories.

2.2 Control of Hybrid Systems

Using as paradigms from Intelligent Vehicle Highway Systems and Air Traffic Control to motivate us we developed a set of techniques for the *hybrid control* of hierarchically organized systems. As discussed in the proposal the need for hybrid control arises because of the interaction between discrete dynamics (event driven) on the higher levels of the hierarchy and continuous dynamics in the lower levels of the hierarchy. We have given essentially complete solutions to the design of hierarchical hybrid control systems and shown their applications to both the prototype applications. Both these systems have important resemblances and similarities to command and control problems in the Army (of the kinf encountered at ARDEC, Picatinny), convoying problems (of the kind encountered at TACOM), and target recognition problems. In more recent work on this grant, we will also consider sensor networks and intelligent control of flying autonomous vehicles.

The publications may be divided as follows:

- Basic theoretical results for hybrid control of multi-agent systems, e.g. [11], [9], [8], [19], [17], etc.
- Hybrid Control of Air Traffic Management Systems, e.g. [6], [7], [12], [4], [10], [5], etc.
- Hybrid Control of Intelligent Vehicle Highway Systems for e.g., [3].

2.3 Hierarchical Descriptions of Hybrid Systems

Here we consider the problem of *consistent abstractions* of hierarchical systems which can be continuous and discrete. The results obtained may be summarized as follows:

- Results on consistent hierarchical models of dynamical and control systems. This generalizes some early work of Wonham, Caines and others on building hierarchical models and lattices of all possible abstractions ([18], [20], [13])
- Results on when nonlinear hybrid automata can be modeled with finite bisimulations. In a set of spectacular papers combining mathematical logic and some very interesting new differential geometry, we give essentially the most exahustive known results in producing decidability results for verifying "safety properties" in hybrid systems. The relevant papers are [12], [19], [17],

In future work on this, we will fully classify all systems for which finite verification can be done both for safety and liveness properties.

2.4 Adaptive Control Systems

Motivated by problems of biological motor control (applications of this are to training troops in new motor skills and also fatigue studies in combat as seen for example at the Army's Natick Laboratories) we have been studying mathematical models for depicting complex motor tasks. While in computer graphics impressive progress has been made in rendering complex scenes, the state of realism of many degree of freedom humans walking, running, diving, is rather rudimentary. We have developed "neurodynamic programming" schemas for hybrid systems involving a combination of continuous and discrete modules to accurately render human actions. The models are accurate right down to the muscular level of participation. The neurodynamic "reinforcement learning" techniques are also applicable to learning of other comples motor systems. Research results in this area are presented in [22], [21], [23], [24].

3 Technology Transfer

During the course of the grant we have interacted with:

1. Dr. Lou Piscitelle of the Army Natick Center on biological motor control and training.
2. Dr. Norman Coleman of ARDEC, Picatinny Arsenal on multi-agent hybrid control systems
3. Dr. Jagdish Chandra, Jose Salinas, and others in the Intelligent Systems Division of the Army Research Laboratories on intelligent control of multi-agent systems

In addition the PI (Sastry) has attended meetings at the ARO on planning (BOG), and other strategic research directions workshops. He has also assisted in Army reviews of other Army research centers.

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